A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

CONF-841219--1

NOTICE

LA-UR--84-1490

DE84 012623

PORTIONS OF THIS REPORT ARE ILLEGIBLE. It has been reproduced from the best available copy to permit the broadest possible availability.

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

TITLE: REFUELING CONSIDERATIONS FOR LIQUID-HYDROGEN FUELED VEHICLES

AUTHOR(S): Walter F. Stewart

SUBMITTED TO: 5th Intersociety Cryogenics Symposium, December 9-13, 1984
New Orleans, LA

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

REFUELING CONSIDERATIONS FOR LIQUID-HYDROGEN FUELED VEHICLES*

Walter F. Stewart

Los Alamos National Laboratory

Los Alamos, NM 87545

ABSTRACT

Liquid hydrogen is a possible fuel for transportation applications in the future. Such use of liquid hydrogen will require a refueling station analogous to today's service station for gasoline and diesel fuels. The cryogenic nature of liquid hydrogen and concerns for safety indicate the desirability of a refueling system that is automated as completely as possible and incorporates sufficient redundancy for safe and reliable operation. A refueling system designed on the basis of previous experience with liquid hydrogen transfer systems has been developed, and a preliminary system has been built and tested. A series of tests was conducted to determine the extent of the liquid hydrogen losses during a refueling operation and to determine optimum transfer procedures and conditions.

---

*Work performed under the auspices of the U.S. Department of Energy.

NOTATION

ARS	Automatic Refueling Station
BLHSD	Bulk Liquid-Hydrogen Storage Dewar
DFVLR	Deutsche Forschungs- und Versuchsanstalt fur Luft- und Raumfahrt
DRS	DFVLR Refueling Station
FFM	Facility Flow Meter
FPS	Facility Pressure Sensor
FRG	Federal Republic of Germany
FV	Facility Valve
FVS	Facility Vacuum Sensor
GH_2	Gaseous Hydrogen
GN_2	Gaseous Nitrogen
HFV	Hydrogen-Fueled Vehicle
LH_2	Liquid Hydrogen
LHVF	Liquid-Hydrogen-Fueled Vehicle
LL	Liquid Level
NASA	National Aeronautics and Space Aministration
NC	Normally Closed (valve position)
NO	Normally Open (valve position)
PR	Pressure
PRV	Pressure Regulator Valve
RV	Relief Valve
SV	Solenoid Valve
VLHD	Vehicle Liquid Hydrogen Dewar
VV	Vehicle Valve
VPS	Vehicle Pressure Sensor
VLS	Vehicle Liquid Sensor

INTRODUCTION

The widespread use of hydrogen as a transportation fuel will involve several major aspects that include:

- a primary energy source to produce hydrogen (hydrogen is an energy carrier, not an energy source);
- a hydrogen production capability;
- a hydrogen storage and distribution capability (a hydrogen liquefaction capability may be included);
- an engine designed or converted for operation with hydrogen;
- a vehicular onboard storage capability;
- safety, economic, and legal considerations.

Each of these major aspects is being, or has been, addressed in varying degrees. This paper will present some refueling considerations for liquid-hydrogen-fueled vehicles (LHFVs) for ground transportation systems. Refueling considerations for the metal hydride onboard storage mode have been given elsewhere, Refs. 1 and 2, for example.

Hydrogen-fueled vehicles (HFVs) require a place and means analogous to today's gasoline service station for refueling. Because a variety of onboard storage systems, such as compressed gas, metal hydrides, and liquid hydrogen (LH_2) are likely to be used, a typical service station will be required to service more than one type of onboard storage unit. At present, each of the projects involving a HFV has developed its own system for refueling the vehicle; however, the widespread use of hydrogen as a vehicular fuel will require that the refueling aspect be addressed more generally and in detail and that the refueling station be standardized as much as possible.

Onboard storage of hydrogen as a liquid is applicable to all types of transportation systems: aircraft, ship, train, bus, truck, and automobile.

Refueling systems for these various transportation modes will have many common elements; consequently, the considerations presented herein will have a broad application. In fact, present and previous programs involving the handling and use of LH_2 provide valuable experience applicable in the design and operation of LH_2 refueling stations for ground transportation vehicles, as for examples, the National Aeronautics and Space Administration (NASA) experience in the Centaur, Apollo, and Space Shuttle prorams[3,4] and the considerations by NASA[5,6] and Lockheed[7] for refueling LH_2-fueled aircraft.

Some of the earliest considerations for refueling LHFVs includes those by Stewart and Edeskuty.[8-10] However, the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) of the Federal Republic of Germany (FRG) was the first to build a special "fueling station" system for refueling LHFVs from conventional LH_2 storage facilities. The DFVLR has built two such refueling stations: the first for use in the DFVLR program in the FRG and the second for use in a joint program with the Los Alamos National Laboratory. The DFVLR refueling concept used in these two refueling stations will be described briefly in this paper; a more detailed description may be found in numerous publications (Refs. 11-15, for example). But first, some of the design considerations for a LH_2-refueling station will be discussed.

LH_2 REFUELING SYSTEM DESIGN CONSIDERATIONS

A LH_2-refueling station must include a bulk LH_2-storage system, a transfer system for both vehicle refueling and bulk resupply, instrumentation, controls, safety equipment, and such ancillary equipment as a gaseous-hydrogen (GH_2) recovery (or safe disposal) system. Two options are available for supplying LH_2 to the refueling station: (1) deliver LH_2 to the station by pipeline, railcar, or truck/trailer; and, (2) liquefy the hydrogen on-site, with GH_2 either generated on-site or delivered to the station by gas pipeline. The transfer of LH_2 from the bulk storage system to the onboard fuel tank can be made by either a pumped or pressure-differential transfer. Also, provisions for a mobile refueling system may be required for the remote refueling of, or removal of fuel from, vehicles away from fixed-location refueling stations. For large-scale uses, such as refueling airplanes or buses, the refueling system may involve the continuous circulation of LH_2 through the system.[5,16]

During a LH_2 transfer from a supply tank to a receiving tank using either a pressure-differential or a pump method, some amount of LH_2 is vaporized and/or lost as a result of the following processes:

- flashing of the saturated liquid in the supply tank to the lower pressure of the receiving tank (pressure-differential method);
- addition of heat as pump-work and other heat leaks associated with a pump (pump method);
- cooldown of the supply-tank pressurization gas (hydrogen or helium), if any;
- cooldown of the transfer lines, refueling station, and receiving tank (if initially warm);
- warm gas from the transfer line entering the receiving tank and vaporizing part, or all, of any LH_2 remaining in the tank from a previous fill;
- heat leak through supports, connections (such as bayonets), and thermal insulation in the storage tank, the receiving tank, the refueling station, and the transfer lines; and
- liquid entrainment in the vent gas from the receiving tank.

The transfer system must be designed to minimize LH_2 losses from these processes. The extent of some of these losses is design-related; for example, the LH_2 loss from liquid entrainment in the vent gas depends upon the design and interface conditions of the fill and vent lines in the receiving tank; consequently, this loss may be avoided in a suitably designed tank.

Several of the loss modes are interrelated. For example, a transfer line with a large inside diameter would permit a larger LH_2 flow rate with less pressure in the supply tank. However, the larger inside diameter would result in a higher initial LH_2 vaporization to cool the increased mass of material; but, compensating for this, the LH_2 vaporization from flashing could be reduced by operating the storage tank at a lower pressure because flow-resistance is reduced.

Some of the losses associated with a pressure-differential transfer may be avoided by using a pump to transfer LH_2 from a storage tank to a receiving tank. However, the use of a pump introduces other problems, such as the need to keep the pump submerged in LH_2 (no gas) and the additional heat leak from the pump. In addition, a pump transfer system is less reliable, more difficult to operate, and more expensive than a pressure-differential transfer system. Some of these losses will be reduced for refuelings after an initial fueling, depending on the time interval between the fueling operations.

As a general rule, the onboard vehicle LH_2 storage dewar (VLHD) must operate at a pressure greater than the ambient atmospheric pressure to prevent air from entering the system (if there is a leak in the system) and to deliver hydrogen to the engine. Some of the factors involved in determining the minimum and the normal operating pressures for an onboard storage tank include -

- the minimum hydrogen pressure required at the engine,
- the pressure drop in the hydrogen delivery system from the tank to the engine,

- potential elevation and barometric pressure changes, and
- operating tolerances in the pressure sensing and control systems.

Most of these factors require only a modest positive pressure level. For example, the engine fuel systems used in the LH_2-fueled Buick at Los Alamos required a normal operating pressure of at least 68.9 kPa at the hydrogen regulator inlet to maintain proper vehicle performance. Consequently, the refueling system and the onboard storage tank should include provisions for maintaining the minimum, and supplying the normal, operating pressures whenever LH_2 is tanked. At the conclusion of a refueling operation, the normal tank operating pressure should be established to avoid a delay in vehicle restart.

A major concern in the design and operation of a refueling station will involve safety. Past experience gained in the design, installation, and operation of LH_2 systems[3,11,12] will have a major influence on future systems. For example, a published assessment of mishaps involving hydrogen[4] provides pertinent design information for future systems. A knowledge of the safety problems involved in an operation of a system is the first step in overcoming or avoiding many potential problems. Such safety considerations in the design and operation of a LH_2 refueling station include:

- safety during refueling and resupply;
- safety devices, safety clothing, and protective equipment;
- safety inside the service station during vehicle maintenance;
- consequences of LH_2 spills in, or near, an inhabited area;
- hydrogen detection and warning system;
- fire protection system;
- vandalism and sabotage protection;
- electrical equipment isolation;

- lightning protection;
- electrical grounding system;
- periodic maintenance and inspection of equipment;
- purging and cleanliness requirements; and
- personnel training program in safe system operation, leak testing, etc.

The cryogenic nature of LH_2 and the concerns for safety (especially in view of the eventual need for operation by personnel with minimal training) suggest that the refueling system should be automated as completely as possible. A computer-controlled system with sufficient redundancy for safety and reliability in all aspects (including sensing and control) may be necessary to provide protection from the most common cause of mishaps--operator error. Even well-trained personnel offer no absolute guarantee of a safe operation: anyone can become lax in performing an often-repeated task. A distraction or an invalid assumption (for example, a valve that is normally closed is assumed to be closed and is not checked) can cause an unsafe condition or operation. The combination of automatically controlled equipment, well-trained personnel, periodic inspection and maintenance, and periodic training sessions are major ways of establishing and maintaining a safe operation.

That safety must be an integral part of the development of hydrogen as a transportation fuel is exemplified by the Hydrogen Safety Program of the National Research Council of Canada, which includes a study of a "liquid hydrogen filling station" with the goal of providing design guidance for such an installation.[16-18]

DFVLR REFUELING STATION (DRS)

The refueling station built by the DFVLR for a joint program with the Los

Alamos National Laboratory was about the size of an ordinary gasoline-service-station pump, was semiautomatic in operation, and was designed to be operated by personnel with little or no special training. The DRS is shown in Fig. 1 in operation at the 53-kℓ LH_2 storage facility at Los Alamos, and in Fig. 2 with a 500-ℓ LH_2 storage dewar.

The DRS semiautomatic refueling procedure provided a "step and check" operation with automatic stops and alarms if discrepancies in the procedure were detected. The operator performed several manual steps: (1) connect the electrical ground wire and the fill and return lines from the DRS to the VLHD; (2) press the "Refueling On" button; (3) open the fill and return valves on the VLHD; (4) close the fill and return valves; (5) press the "Tank Valves Closed" button; and (6) disconnect the fill and return lines and the electrical ground wire. The DRS controlled other functions, such as purging and starting and stopping the LH_2 transfer.

As part of a joint program between the DFVLR and the Los Alamos National Laboratory, a series of tests was conducted at Los Alamos to determine the extent of the LH_2 losses during a refueling operation and to determine optimum transfer procedures and conditions.[19] In these tests, the pressure in the LH_2 supply dewar was varied from 22.7 to 172.4 kPa gauge. The corresponding transfer times ranged from 48 to 9 min. to fill the 110-ℓ dewar in the vehicle. The LH_2-transfer losses in these tests did not change significantly as a function of the transfer time (which was dependent on the transfer pressure and flow rate). Refueling efficiencies* of 73 to 93% were obtained in these tests; the lower efficiency was for filling a warm VLHD and the higher efficiency was for filling a cold VLHD without using the DRS.

---

*The refueling efficiency is defined as the amount of LH_2 accumulated in the VLHD divided by the total amount removed from the BLHSD.

In a typical filling test of a cold VLHD without the DRS, 8.7 ℓ of LH_2 was lost (vaporized). Of this amount it was estimated, on average, that 0.8 ℓ was vaporized as a result of heat leak into the system, 1.9 ℓ was vaporized in cooling down the transfer lines, and 6 ℓ vaporized as a result of other factors such as cooldown of the pressurization gas and flashing (which was probably the most significant loss).

AUTOMATIC REFUELING SYSTEM CONCEPT

On the basis of the design considerations discussed earlier and the operating experience available, and for reasons of safety, operator training requirements, operating convenience, and minimization of LH_2 losses, a fully integrated LH_2 automatic refueling system (ARS) concept was developed.[19] The ARS design eliminated a separate refueling station (such as the DRS) and incorporated transfer controls as part of the LH_2 storage tank. The transfer system was integrated further by de- signing the VLHD so that the appropriate valves and instrumentation required in the VLHD could be used functionally as a part of the refueling system, thus simplifying the system.

The ARS concept that was developed involved the following major subsystems:

- bulk LH_2 storage;
- LH_2 transfer;
- facility LH_2 resupply;
- GH_2 storage;
- hydrogen recovery;
- hydrogen disposal;
- purge-gas storage (nitrogen or helium, or both);
- transfer system purge or evacuation;
- facility master-control; and
- refueling-port control (for each refueling port).

The bulk LH_2 storage subsystem could be one or more dewars for bulk LH_2 storage and from which LH_2 is transferred to a VLHD. The LH_2 transfer subsystem would comprise those components necessary to transfer liquid from a BLHSD to a VLHD and a flow meter to measure the quantity transferred. The facility LH_2 supply subsystem would resupply the BLHSD from mobile LH_2 tankers, or other sources, as needed. The GH_2 storage subsystem would supply GH_2 for purging and pressurization requirements.

A substantial quantity of GH_2 would be available from such processes as transfer line cooldown. Subject to economic considerations, this relatively pure GH_2 could be recovered and stored for use in a variety of ways (for example, for purge and pressurization, or as a fuel to provide electrical power, or heat, for the service station). The hydrogen could be reliquefied and returned to the BLHSD if a suitable liquefier were available.* Hydrogen that is not relatively pure (contains some nitrogen or air) could be purified and recovered rather than being vented.

The hydrogen disposal subsystem would safely dispose of all hydrogen that must be vented and would be capable of handling a wide range of hydrogen vent rates to cope with both routine and emergency venting requirements. The purge-gas storage subsystem would provide a supply of gaseous nitrogen (GN_2) and/or helium for meeting purging and pressurization requirements. These inert gases would be used to provide an inert atmosphere in the system whenever it was necessary to open the system or to prevent air and moisture from entering the system. The quantity of helium (a somewhat scarce, expensive material) used should be minimized or eliminated completely, if possible.

---

*The magnetic liquefier under research and development at the Los Alamos National Laboratory might meet this need satisfactorily.[20]

Before hydrogen is admitted into the transfer system (or any part of the M.S.) any impurities, such as air or nitrogen, must be removed from the system. Likewise, after any system has had hydrogen in it, the hydrogen should be removed and replaced with an inert gas (GN_2 for example) before the system is opened. These requirements can be satisfied with either a pressure/purge process or an evacuation process. On the one hand, in purging a container in which hydrogen is present, the pressure/purge process involves several cycles of pressurizing the system with an inert gas, venting the gas, and repeating these two steps until the concentration of hydrogen is reduced to an acceptable level. On the other hand, if one is preparing to admit hydrogen into the system, the pressure/purge process is similarly accomplished with GH_2 until the inert-gas concentration is reduced to an acceptable level. The alternative evacuation process involves using a vacuum pump to evacuate the system and then "breaking the vacuum" by admitting an inert gas (if the system is being inerted) or with hydrogen (if the system is being prepared for hydrogen use). One disadvantage of the evacuation process is that the pressure in the system is less than the ambient pressure during evacuation and air could be pulled into the system if a leak exists. Either process can give an indication that connections, such as bayonets, are or are not properly connected and are not leaking.

The facility master-control subsystem would provide the necessary controls, instrumentation, and alarms to accomplish safely the various necessary operations and processes and to indicate any unsafe condition that develops. All the remotely actuated valves in the facility would be operated by the facility master-control subsystem, which would also contain the necessary controls to operate the facility valves in the proper sequence to accomplish the various processes (for example, evacuation, LH_2 transfer, and purging). In addition, the facility master-control subsystem would receive commands from the refueling-port control subsystem, implement these commands if the facility is ready, and relay data back to the refueling-port control subsystem. If multiple refueling-port control subsystems are involved, the facility master-control subsystem would keep these integrated properly, the facility systems sequenced properly, and prevent an operation from beginning, or proceeding, if unsuitable conditions exist, or develop, during the operation. The refueling-port control subsystem would provide local facility controls and displays for a vehicle refueling operation. A separate refueling-port control box would be provided for each ARS refueling port in a multiple port system.

Numerous design variations are possible in the ARS design, for example; pump transfer, pressure-differential transfer, separate individual LH_2 fill and return lines, single combined coaxial LH_2 fill and return line, bayonet connections, self-sealing quick-disconnect connections, etc. Some of these variations are illustrated in the representative ARS configuration schematics given in Figs. 3 through 5 (other configurations are described in Ref. 19):

- an ARS with separate fill and return lines, bayonet connections, and a pressure-differential transfer system is shown in Fig. 3;
- an ARS with separate fill and return lines, quick-disconnect connections, a pressure differential transfer system, and three separate refueling ports is shown in Fig. 4; and
- an ARS with a single combination coaxial LH_2 fill and return line, bayonet connection, and a pressure-differential transfer system is shown in Fig. 5.

The widespread use of LH_2 as a vehicular fuel will require a capability for refueling vehicles remote from refueling stations at fixed sites. For this purpose, a mobile LH_2 storage and refueling system concept was developed.[19] The variations in the design of an ARS, as mentioned above, also apply to the mobile unit. The mobile LH_2 storage and refueling system could be skid-mounted so that it could be installed on a flat-bed truck or trailer, and it could be set up in a semipermanent location if desired. The mobile unit would be completely self-contained. For safety, it may be necessary to remove all LH_2 from a VLHD before a vehicle is put into a garage or shop for an extended period (even overnight if the facility is unattended or not properly alarmed and ventilated). The mobile unit would provide a convenient method for detanking before, and refueling after, repairs are made.

A block diagram of how an ARS with two refueling ports might be arranged is shown in Fig. 6. An example layout of a service station with two BLHSDs is shown in Fig. 7. In the arrangement shown in Fig. 7 the BLHSDs are 7.6 m from a roadway and 22.9 m from a building, in accordance with existing safety standards.

A typical refueling sequence for an operational ARS, as shown in Fig. 3, would proceed according to the following steps:

1. The operator connects the electrical control cable from the refueling-port control box to the mating connector on the vehicle after checking the "ready" light on the box is lit -- indicating that the facility and the port are ready to transfer LH_2.
2. The operator removes the two transfer lines from their holder and connects them to the ports on the VLHD. The two transfer lines are fastened together and arranged in such a way that they would be installed in the proper ports. A snap latch would hold the lines in place during refueling, and a cover cap would be snapped over the VLHD refueling ports when the vehicle was not being refueled.
3. After selecting the quantity of hydrogen desired the operator presses the "start" button on the refueling-port control box.

4. The refueling-port control box verifies that the vehicle is ready (valve VV1 is in the normally-open (NO) position, and valves VV2, VV3, and VV4 are closed.)
5. The "start" signal and the "vehicle ready" indication are relayed from the refueling-port control box to the facility master-control box, where the facility "ready" is verified.
6. The vacuum pumping system is activated, facility valves FV9 and FV10 are opened, and the fill and return lines are evacuated.
7. If a preset vacuum level (as indicated by FVS2 and FVS3) is achieved within the preselected time interval (indicating that the connections at the vehicle are not leaking), valves FV9 and FV10 are closed, the vacuum pumping system is deactivated, and vehicle valve VV2 is opened, allowing hydrogen from the VLHD to enter the fill and return lines.
8. Facility valve FV21 is opened and GH_2 from the VLHD is recovered while the VLHD is vented to near atmospheric pressure.
9. When the VLHD pressure is proper [as indicated by the vehicle pressure sensor (VPS)], facility valve FV1 opens and LH_2 flows from the BLHSD through the facility flow meter (FFM), the fill line, the normally open path of vehicle valve VV1, the return line, and valve FV21 to the recovery system. As LH_2 flows along this path it is initially vaporized until the path is cooled to about 20 K. Depending on the flow meter type, it may be necessary to use valve FV2 rather than FV1 during the cooldown phase.
10. When LH_2 is sensed by the vehicle liquid sensor (VLS), vehicle valve VV1 is actuated and LH_2 flows into the VLHD after cooldown of the line from VV1 into the tank.

11. LH_2 continues to flow in this configuration until the desired amount has been transferred into the VLHD and the "stop" signal is given manually or automatically. GH_2 from heat leak, flashing, etc. is recovered throughout the transfer process.

12. When the "stop" signal is received, vehicle valve VV1 returns to its normally open position, facility valve FV1 closes, and vehicle valve VV2 closes.

13. At this point, the fill line still contailns some LH_2 that must be removed by some method, such as gravity drain into the return line or by a GH_2 purge by opening facility valve FV19 for a preselected time.

14. After the LH_2 is removed from the fill and return lines, the recovery valve FV21 is closed and the GH_2 is removed from the lines by activating the vacuum pumping system and opening facility valves FV9 and FV10. It may be necessary to purge the vent system by having FV12 open for a short time before the hydrogen is pumped from the system.

15. When a preselected vacuum level is reached (as indicated by FVS2 and FVS3), valves FV9 and FV10 are closed and the vacuum system is deactivated.

16. The fill and return lines are pressurized with GN_2 by opening facility valves FV14 and FV15. The use of nitrogen rather than helium for this purpose depends upon the temperature and heat capacity of the metal in the system and the gas; it is necessary that the gas not be solidified or liquefied in the lines or at cold valves, such as FV1.

17. When a preselected pressure, as indicated by the facility pressure sensors FPS2 and FPS3, is obtained in the fill and vent lines, the operator is signaled to disconnect the fill and return lines and the electrical control cable.

18. The operator removes the fill and return lines from the vehicle, snaps the port-cover caps in place, and places the lines in their holder. While the lines are disconnected from the vehicle, the GN_2 purge is continued to prevent air and moisture from entering the cold lines. When the lines are installed in their holder, the pressure in the lines (as indicated by the facility pressure sensors FPS2 and FPS3) increases until the preselected value is reached, and then valves FV14 and FV15 are closed.

19. The operator removes the electrical control cable from the vehicle and presses the "refueling completed" button on the refueling-port control box.

20. As the transfer system warms, the pressure within the system will increase. Facility valves FV7 and FV8 will be actuated to vent GN_2 from the system and maintain the pressure within the preset limits. Alternatively, relief valves or pressure regulators can be used to maintain the desired pressure.

The ARS would include such other components and subsystems as required for other functions, such as LH_2 resupply and detanking of a vehicle or a mobile LH_2 storage unit. The use of a self-sealing quick-disconnect would eliminate several of the above steps, such as the evacuation and purging before and after each refueling. But such a quick-disconnect, which must operate at 20 K, is not available. Also, the quick-disconnect adaptor/holder must include provisions for removal of moisture that would freeze to the surface of the disconnect when it is moved from the vehicle to the holder after a refueling operation.

The ARS configurations that were developed are flexible in that their sizes can be matched with a particular application; the ARS could be sized for a large vehicle, such as a truck or bus, or for a small vehicle, such as an automobile. The primary difference would be in the size of the LH_2 fill and return lines. For example, assume that a car with a 150-ℓ tank and a bus with a 1500-ℓ tank are to be refilled in a total of 5 min from start to finish. Also, assume that 2 min of this time are used in connecting and disconnecting the trasfer lines and cables and in the purging and cooldown processes. Therefore, with 3 min for the liquid transfer, a hydrogen flow rate of 50 ℓ/min for the car and 500 ℓ/min for the bus would be required. These vehicles can probably both be refueled with transfer lines of the same length, say 3 m. Under these conditions, the inside diameter of the LH_2 transfer line would be about 40.6 mm and 17.0 mm for the 500- and 50- ℓ/min flow rates, respectively. During cooldown at the start of a refueling operation, the LH_2 flow rate will be limited by the GH_2 flow through the fill line. As the cooldown progresses, the flow restriction passes from the fill line to the return line. Thus, the return line (both within the VLHD and the facility) must be adequately sized to avoid an undue restriction on the cooldown and refueling rate. During cool-down, most of the GH_2 is produced as a result of cooling the materials in the transfer line, with some lesser amount produced as a result of flashing and heat leak. After cooldown is completed, flashing is the major source of the GH_2 that must be handled by the return system, with a lesser amount resulting from heat leak.

The optimum refueling time needs further study to be established. In some cases 30 min (or even more) would be satisfactory, while in others, 5 min may be necessary. In the widespread public use of hydrogen as a fuel, the number of refueling stations and the number of refueling ports at each would be major factors to be considered, and only short waiting and refueling times would be acceptable.

CLOSING REMARKS

A LH_2 refueling (or service) station analogous to today's gasoline or diesel servilce station can be built to fill a hydrogen storage tank onboard a vehicle safely, efficiently, and in a ime comparable to current gasoline or diesel vehicle refueling time; it can be built using existing technology and commercially available equipment. However, a number of items still require either improvement or further development for this application (for example, an accurate amount-filled measurement for accounting/billing purposes).

A fleet operation is considered to be the most likely entry point for LH_2 into the ground transportation sector; one reason being a limited storage and refueling system can be set up and controlled by trained personnel, whereas a LH_2 refueling system for the general public would require an extensive network of LH_2 refueling stations with a greater possibility of operation by personnel with less training. Further, such stations would tend to be located within more populated areas. If successful, the operation of vehicle fleet refueling systems could provide the experience necessary to expand the use of LH_2 as a fuel.

Safety is a concern frequently expressed in connection with the use of hydrogen (especially LH_2) as a fuel. Gasoline, the fuel with which hydrogen is usually compared, was once the subject of similar concern, as expressed in the following excerpt from the 1875 Congressional Record:

"A new source of power...called gasoline has been produced by a Boston engineer. Instead of burning the fuel under a boiler, it is exploded inside the cylinder of an engine...

"The dangers are obvious. Stores of gasoline in the hands of people interested primarily in profit would constitute a fire and explosive hazard of the first rank. Horseless carriages propelled by gasoline might attain speeds of 14, or even 20 miles per hour. The menace to our people of this type hurtling through our streets and along our roads and poisoning the atmosphere would call for prompt legislative action even if the military and economic implications were not so overwhelming... [T]he cost of producing [gasoline] is far beyond the financial capacity of private industry... In addition, the development of this new power may displace the use of horses, which would wreck our agriculture..."

It is generally recognized (although perhaps many times forgotten) that gasoline is hazardous, as illustrated by the following warning taken from the Consumer Product Safety Commission booklet, "Gasoline is made to Explode:"

"There is no safe way to store gasoline. Vapors from gasoline stored in the home can be ignited by a flame, a spark, or even a hidden pilot light. When you carry gasoline in your car trunk, vapors are likely to fill the trunk. If this vapor is ignited by a collision or by exposure to flame or spark, a fatal explosion could result."

Although this warning is not directed at gasoline tanks onboard vehicles, these are by no means completely safe either--as many as 2000 to 3500 Americans are burned to death every year, according to an estimate by the U.S. Transportation Department, or 600 to 700 according to an estimate of the Ford

Motor Company. Despite the danger, gasoline is routinely handled without reluctance or too much concern by most Americans. The transfer of 76 ℓ of gasoline in a period of 4 min to fill the gasoline tank in the family car involves handling a power equivalent of about 10 MW--yet this is a common event for people without any special training and they do so at facilities with very little in the way of safety equipment.

Thus, we have on the one hand a fuel, gasoline, with which we are all familiar, handle frequently, and perceive to be safe. On the other hand is hydrogen, a fuel that is relatively [illegible]amiliar except for association with the hydrogen bomb (a misnomer) and th[illegible]burg fire in which 38 lives were lost --mostly as a result of jumping from [illegible]oo high or from the diesel fuel fires. It should be remembered that 65 people onboard the Hindenburg survived, and even more significantly, the hydrogen-filled Graf-Zeppelin made regular and safe crossings of the Atlantic in passenger service from 1928 until 1937.

The above items are mentioned to illustrate that safety concerns with unfamiliar substances or processes are, in some cases, unfounded, sometimes based on a lack of knowledge, and are often blown out of proportion to the risk. In the case of existing fuels, safety problems are sometimes unrecognized or overlooked because of over-familiarity.

Hydrogen (both gaseous and liquid) can be safely produced, stored, and handled, as demonstrated by NASA in the space program, by the industrial gas industry supplying hydrogen routinely, and by the ever-increasing use of hydrogen in various commercial and industrial applications. Hydrogen, including LH_2, is routinely handled in a manner that is quite similar to that required in a refueling station. Thus, the LH_2 refueling station represents a new application of an established technology and capability.

REFERENCES

1. Van Vorst, W. D. and Woolley, R. L., "Hydrogen-fueled surface transportation," in Hydrogen: Its Technology and Implications, Cox, K. E. and Williamson, K. D., Jr., Eds., CRC Press, Boca Raton, Florida, 1979, pp. 2-70
2. Buchner, H., "Hydrogen use-transportation fuel," in Hydrogen Energy Progress IV, Vol. 1, Veziroglu, T. N., Van Vorst, W. D., and Kelley, J. H., Eds., Pergamon Press, New York, 1982, pp 3-29.
3. Bain, A. L., "NASA Space Program Experience in Hydrogen Transportation and Handling," Int. J. Hydrogen Energy, Vol. 1, No. 2, June 1976, pp. 173-188.
4. Ordin, P. M., "Review of Hydrogen Accidents and Incidents in NASA Operations," in Proc. 9th Intersociety Energy Conversion Engineering Conference, ASME, New York, 1974, pp 442-453.
5. Korycinski, P. F., "Air Terminals and Liquid Hydrogen Commercial Air Transports," in Int. J. Hydrogen Energy, Vol. 3, No. 2, June 1978, pp. 231-250.
6. Small, W. J., Fetterman, D. E., and Bonner, T. F., Jr., "Alternate Fuels for Transportation, Part I: Hydrogen for Aircraft," Mechanical Engineering, Vol. 96, No. 5, May 1974, pp. 18-24.
7. Brewer, G. D., "The Prospects for Liquid Hydrogen Fueled Aircraft," Int. J. Hydrogen Energy, Vol. 7, No. 1, January 1982, pp. 21-41.
8. Stewart, W. F. and Edeskuty, F. J., "Alternate Fuels for Transportation, Part 2: Hydrogen for the Automobile," Mechanical Engineering, Vol. 96, No. 6, June 1974, pp. 22-28.
9. Edeskuty, F. J., "Long Range Considerations and Possibilities of a Hydrogen Economy," address to the Compressed Gas Association, Jan. 28, 1974, San Francisco, CA, Los Alamos Scientific Laboratory report LA-UR-74-528.

10. Stewart, W. F., "Liquid Hydrogen as [illegible]omotive Fuel," in *Advances in Cryogenic Engineering*, Vol. 25, K. D. Timmerhaus and H. A. Snyder, Eds., Plenum Press, NY, 1980, pp. 822-830.

11. Peschka, W., "Operating Characteristics of a LH_2-Fueled Car and of a Semiautomatic LH_2 Refueling Station," in *Hydrogen Energy Progress*, Vol. 3, T. N. Veziroglu, K. Fueki, and T. Ohta, Eds., Pergamon Press, New York, 1980, pp. 1561-1576.

12. Stewart, W. F. and Escher, W. J. D., "Liquid-Hydrogen Automotive Onboard Storage and Servicing System Project: A Progress Report," in *Alternative Fuels*, Vol. SP-480, Society of Automotive Engineers, Warrendale, Pennsylvania, 1981, pp. 181-188.

13. Peschka, W. and Carpetis, C., "Cryogenic Hydrogen Storage and Refueling for Automobiles," *Int. J. Hydrogen Energy*, Vol. 5, No. 5, December 1980, pp. 619-625.

14. Peschka, W. and Carpetis, C., "Cryogenic Hydrogen Storage and Refueling for Automobiles," in *Proc. 14th Intersociety Energy Conversion Engineering Conference*, Vol. 1, American Chemical Society, Washington, D.C., 1979, pp. 763-767.

15. Peschka, W., Edeskuty, F. J., and Stewart, W. F., "Liquid-Hydrogen Storage and Refueling for Automotive Applications," in *Alternative Energy Sources III*, Vol. 5, Hemisphere Publishing Corp., Washington, 1983, pp. 407-417.

16. Jones, N. G. L., "A Schematic Design for a HAZOP Study on a Liquid Hydrogen Filling Station," *Int. J. Hydrogen Energy*, Vol. 9, No. 1/2, February 1984, pp. 115-121.

17. Knowlton, R. E., "An Investigation of the Safety Aspects in the Use of Hydrogen as a Ground Transportation Fuel," *Int. J. Hydrogen Energy*, Vol. 9, No. 1/2, February 1984, pp. 129-136.

18. Knowlton, R. E., "An Investigation of the Safety Aspects in the Use of Hydrogen as a Ground Transportation Fuel," to be published in proceedings of the 5th Intersociety Cryogenics Symposium, 1984.

19. Stewart, W. F., "Experimental Investigation of Onboard Storage and Refueling Systems for Liquid-Hydrogen-Fueled Vehicles," Report DOE/CE-0039, U.S. Department of Energy, Washington, D.C., September, 1982.

20. Barclay, J. A., "Can Magnetic Refrigerators Liquefy Hydrogen at High Efficiency?" ASME paper 81-HT-82, presented at the 20th Joint ASME/AIChE National Heat Transfer Conference, Milwaukee, Wisconsin, August 2-5, 1981.

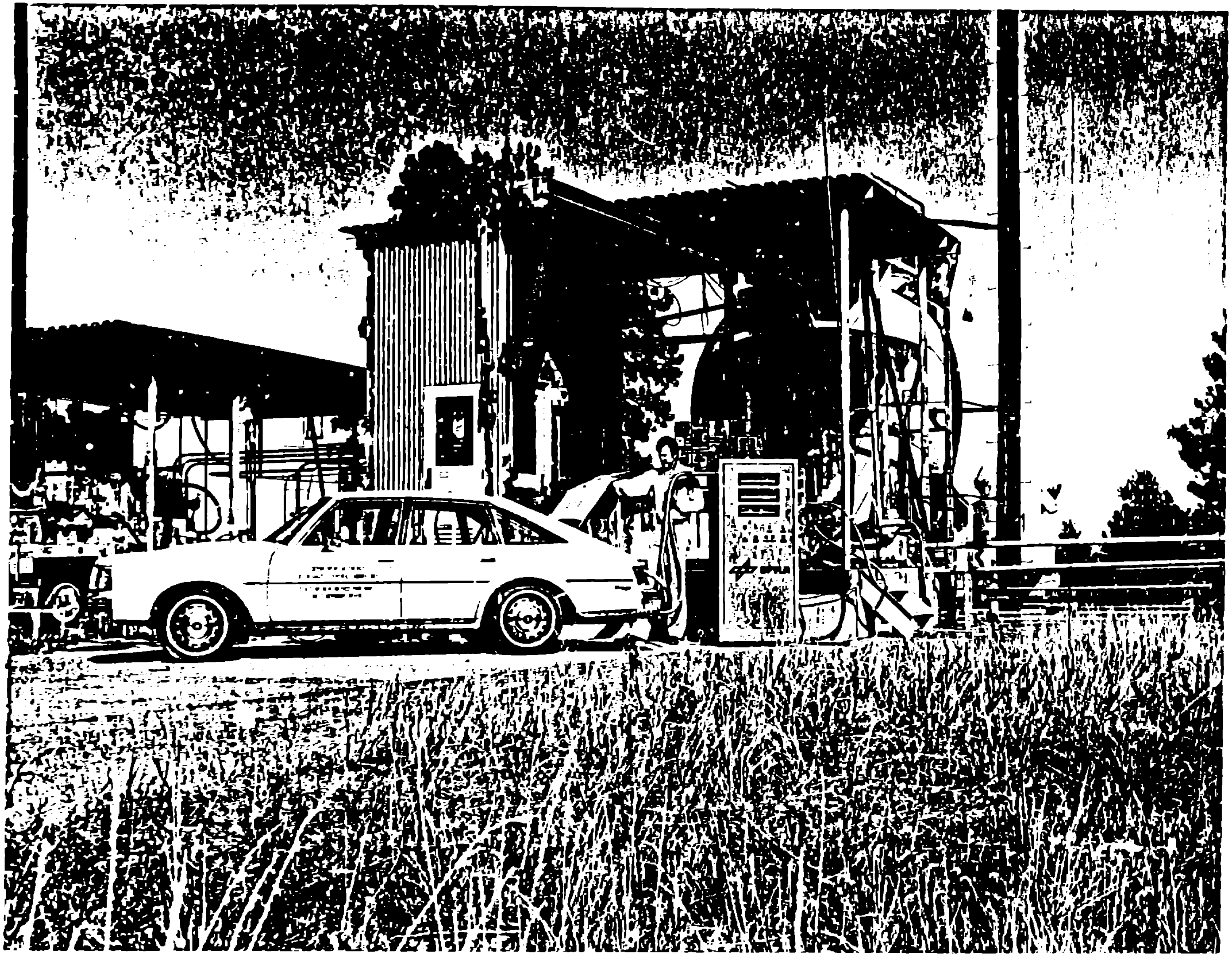

Fig. 1. Refueling operation at the 53kℓ liquid-hydrogen supply facility at Los Alamos.

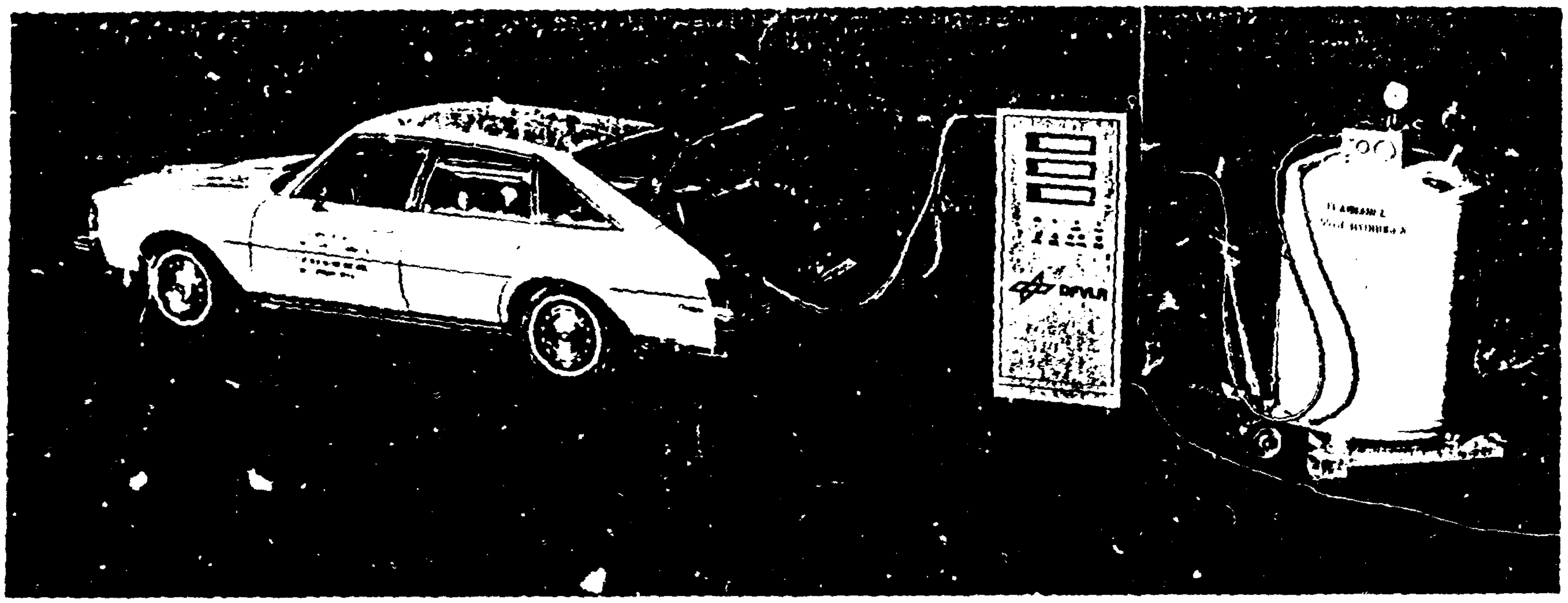

Fig. 2. Refueling operation with the DRS and a 500-ℓ liquid-hydrogen supply dewar.

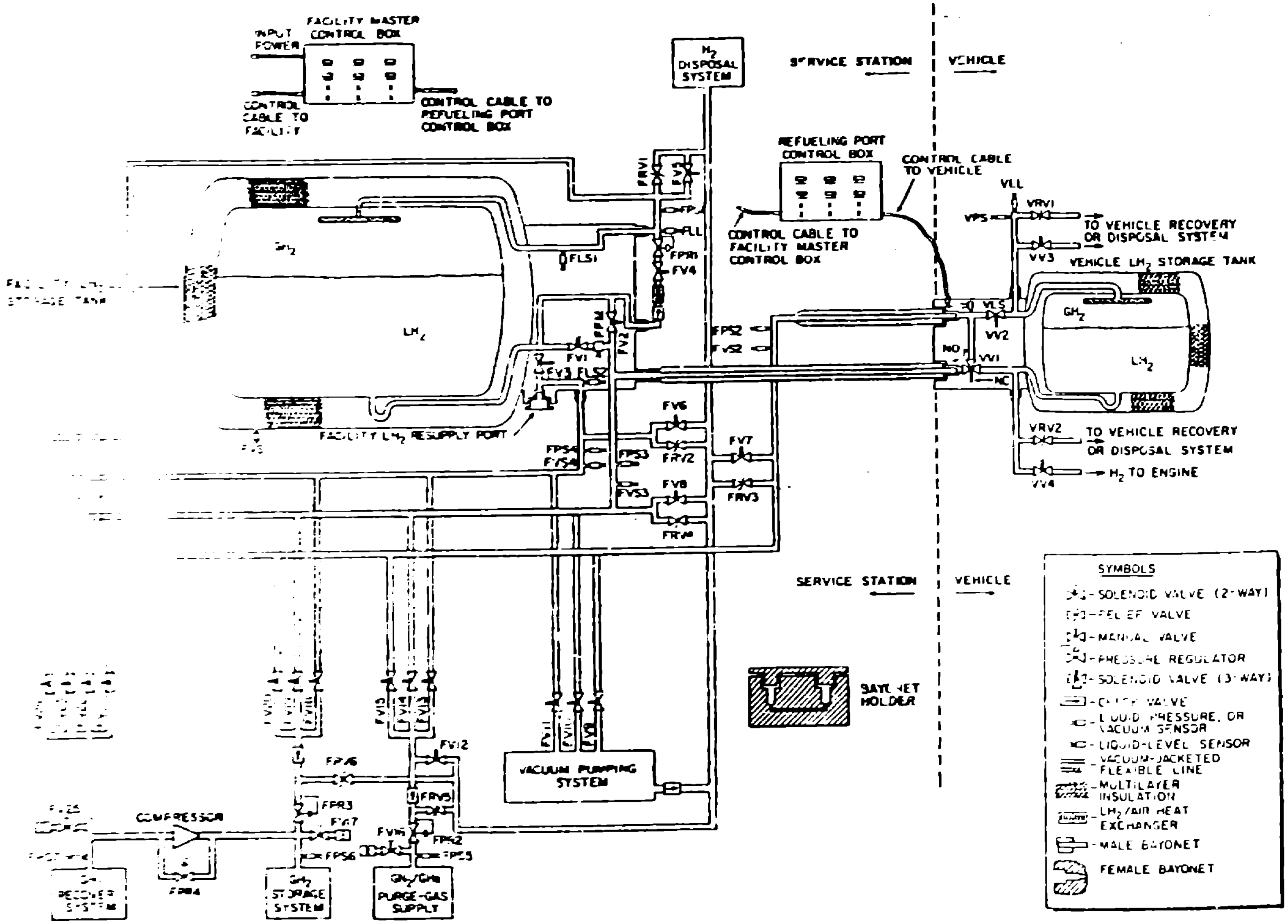

Fig. 3. Fully integrated ARS with separate fill and return lines, bayonet connections, and a pressure-differential transfer system.

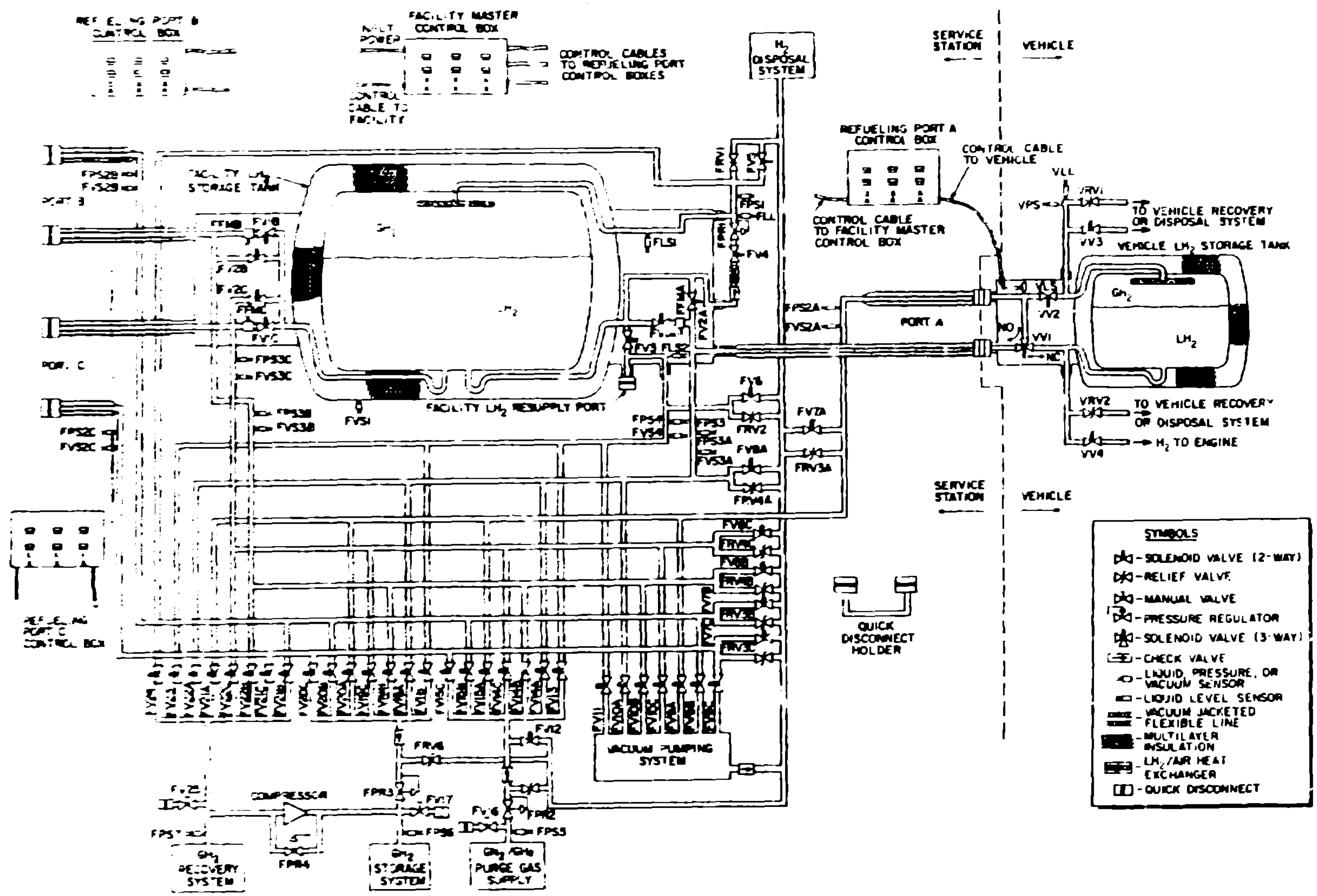

Fig. 4. Fully integrated ARS with separate fill and return lines, quick-disconnect connections, a pressure-differential transfer system, and three separate refueling ports.

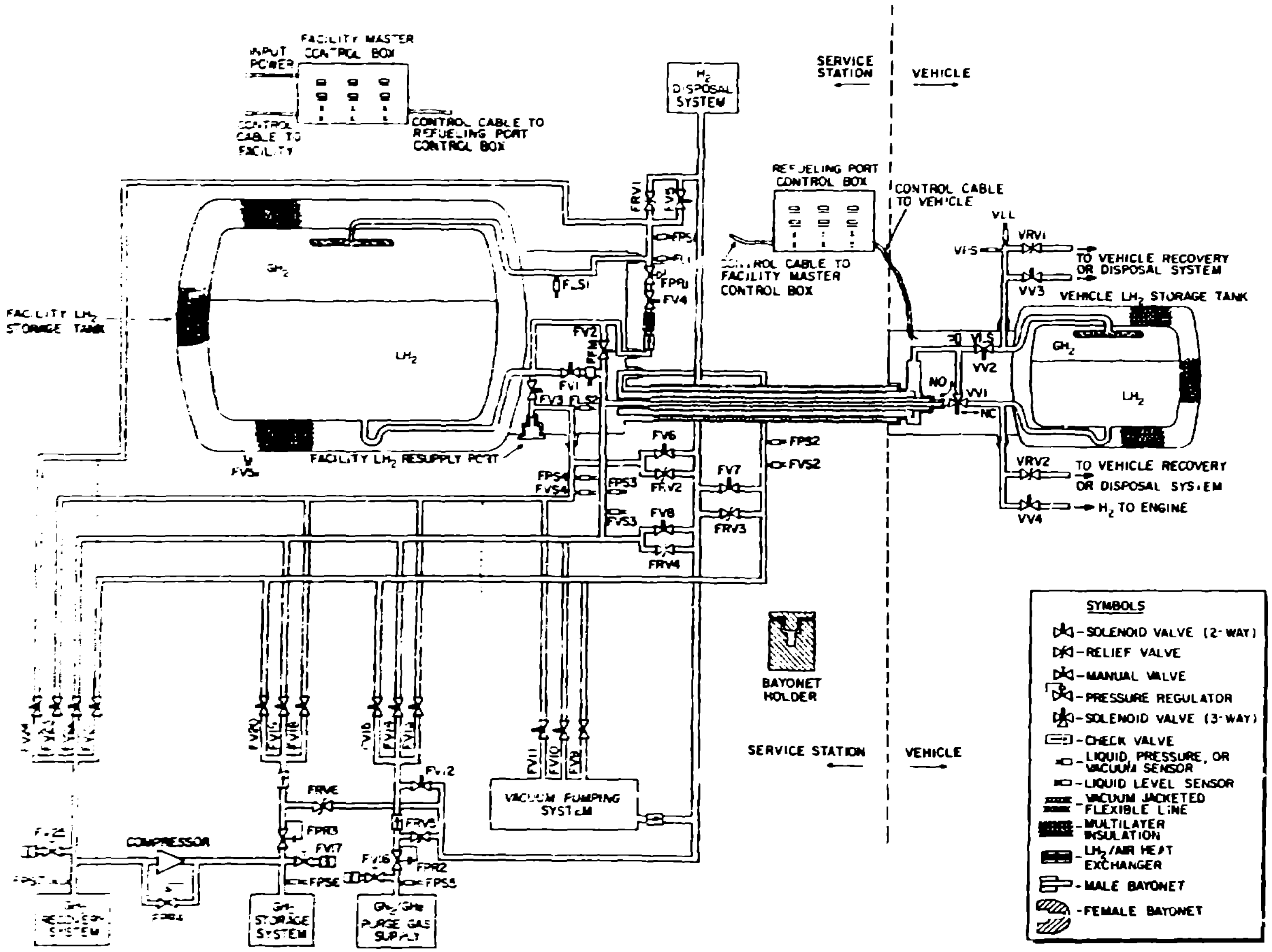

Fig. 5. Fully integrated ARS with a single combination coaxial liquid-hydrogen fill and return line, bayonet connection, and a pressure-differential transfer system.

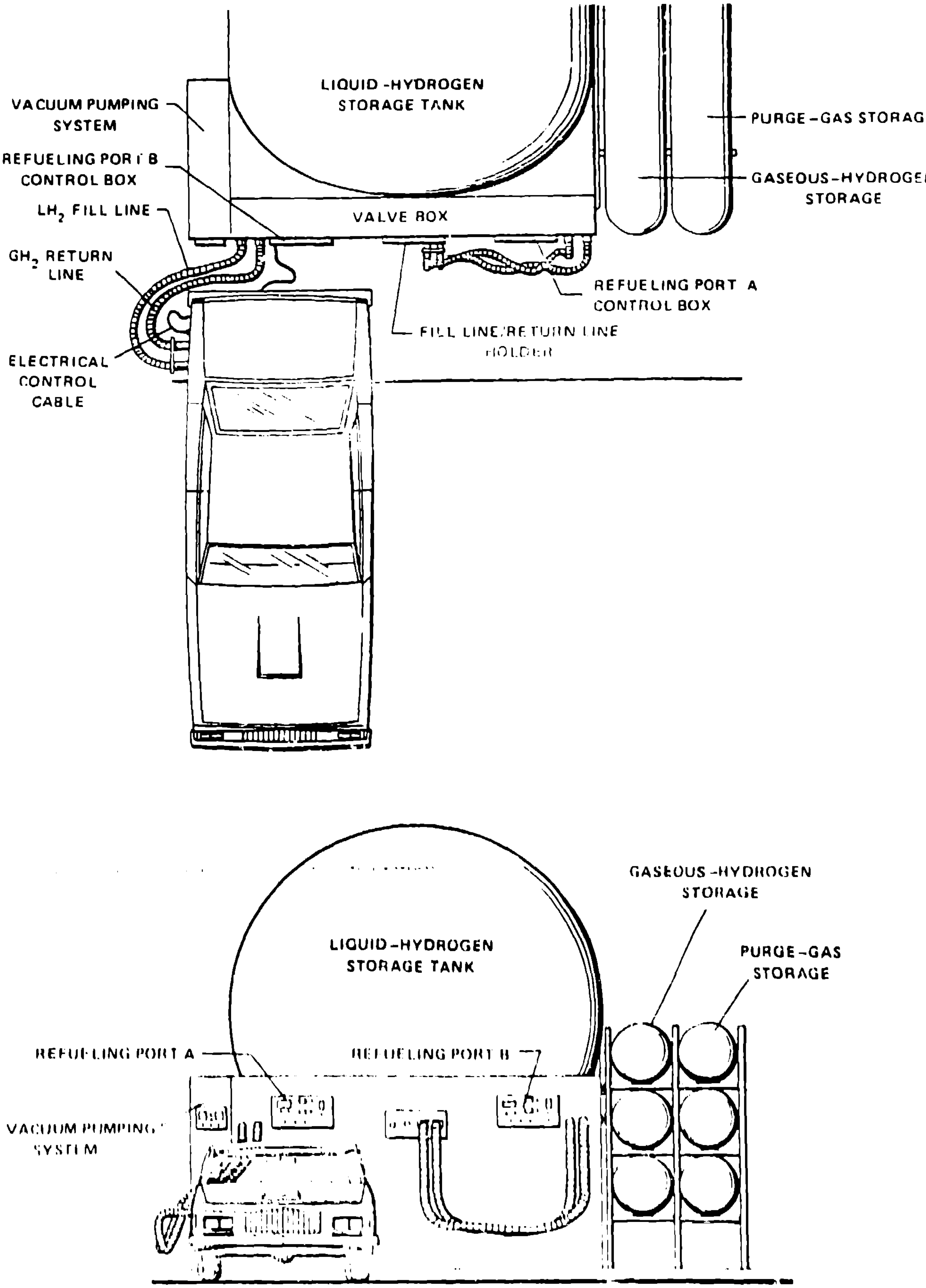

Fig. 6. Possible ARS arrangement.

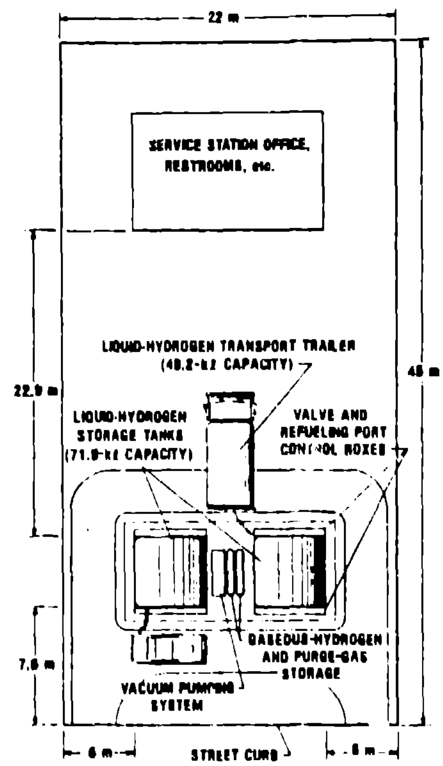

Fig. 7. Layout of a liquid-hydrogen service station